Thermally induced pressures in an on-farm grain storage bin

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Zhang, Q., Britton, M.G. and Leitgeb, J.M. 1993. **Thermally induced pressures in an on-farm grain storage bin**. Can. Agric. Eng. **35**:051-055. Thermally induced lateral pressures on the bin wall were measured around the circumference (0.9 m above the bin floor) of a corrugated-steel bin (5.8 m in diameter, 6.2 m high). The bin was filled with wheat at 10.0 % moisture content (wet basis) to a depth of 5.0 m. Observed lateral pressures varied diurnally, with lower pressure during the daytime and higher pressure during the nighttime. The distribution of thermal pressure around the bin circumference was non-uniform during the daytime hours and was uniform during the nighttime hours. The thermal pressure per unit decline in wall temperature did not vary significantly ($P<0.05$) around the bin circumference during either the daytime or the nighttime hours. The average thermal pressure increment was 114 Pa/°C for a range of bin wall temperature from -11 °C to -29 °C.

Les pressions latérales induites thermiquement sur le mur d'un réservoir en acier ondulé (5.8 m de diamètre, 6.2 m de hauteur) ont été mesurées autour de sa circonférence (0.9 m au-dessus du plancher du réservoir). Le réservoir était rempli à une hauteur de 5.0 m avec du blé à 10.0% de teneur en humidité (base humide). Les pressions latérales observées variaient durant la journée, et étaient plus basses durant le jour et plus élevées durant la nuit. La distribution de la pression latérale autour de la périphérie du réservoir était non-uniforme durant le jour et était uniforme durant la nuit. La pression thermique par baisse unitaire de la température du mur n'a pas varié significativement ($P< 0.05$) autour de la périphérie du réservoir, que ce soit durant le jour ou durant la nuit. L'incrément moyen de pression thermique a été de 114 Pa/°C pour des températures du mur du réservoir variant entre -11°C et - 29°C.

INTRODUCTION

Lateral pressures on the walls of filled metal grain storage bins increase when bins are subjected to declining ambient temperature (Britton 1973; Manbeck and Muzzelo 1985; Blight 1985; Puri et al. 1986). When a metal bin is subjected to a rapidly declining ambient temperature, the bin wall temperature decreases accordingly, causing the wall to contract, whereas the temperature of stored grain does not change as rapidly as the steel wall (Manbeck and Britton 1988). Therefore, the bin wall contraction is resisted by the stored grain. The resisting force from the grain causes an increase in lateral pressure on the bin wall. This increase in lateral pressure is termed thermal pressure (or thermally induced pressure). Several models and methods have been developed for predicting thermal pressures (Andersen 1966; Manbeck 1984; Thompson and Ross 1984; Zhang et al. 1987). One of the assumptions underlying the existing theories is that thermal loading is symmetric, i.e., the thermal pressure does not vary around the bin circumference. In on-farm grain bins, however, wall temperatures are pronouncedly dependent on the wall orientation (Manbeck and Britton 1988). This raises a question on the uniformity of thermal pressure distribution around the bin circumference because uneven wall temperature may cause non-uniform wall contraction. The objectives of this study were: (1) to measure lateral pressures and wall temperatures in an on-farm grain storage bin; and (2) to examine the distribution of thermal pressure around the bin circumference.

EXPERIMENT AND PROCEDURE

Test facility

The experiment was conducted using a commercial grain storage bin (Westeel Model 198, Westeel, Winnipeg, MB) located on a farm 30 km west of Winnipeg, MB. The corrugated galvanized steel bin had a diameter of 5.8 m and an eave height of 6.2 m. The details of the test bin were described by Leitgeb (1990). The bin was filled with hard red spring wheat to a depth of 5.0 m (measured from the floor to the apex of the conical grain surface) (Fig. 1). Physical properties of the wheat are summarized in Table I. Bulk density and moisture content were determined by following the procedures recommended by the Canadian Grain Commission standards (Anon 1984), and by ASAE standards S352.2 (ASAE 1989), respectively. Grain-wall friction was measured using the tilting table method described by Kukelko et al. (1988). The angle of repose was determined from the measured height of grain heap after the bin was filled.

Diaphragm sensors were used to measure lateral pressures on the bin wall. Six sensors were placed 60° apart on the inside surface of the bin wall around the bin circumference, 0.9 m above the concrete foundation (Fig. 1). Sensors were numbered clockwise with Location 1 coinciding with the magnetic north. Each sensor was glued to the wall flush with the corrugation. The effects of thermal expansion or contraction of the wall on sensors was minimum because: (1) glue provided a highly elastic bond between sensors and the wall; and (2) sensors experienced similar temperature changes as did the wall. A thermocouple was attached to each of the six sensors for measuring sensor temperatures, which were later used for compensating temperature induced strains. Another set of six thermocouples was affixed on the inside wall surface for measuring wall temperatures near the pressure sensors (Fig. 1). To monitor changes in grain temperatures, five thermocouples were placed in the grain mass at the same

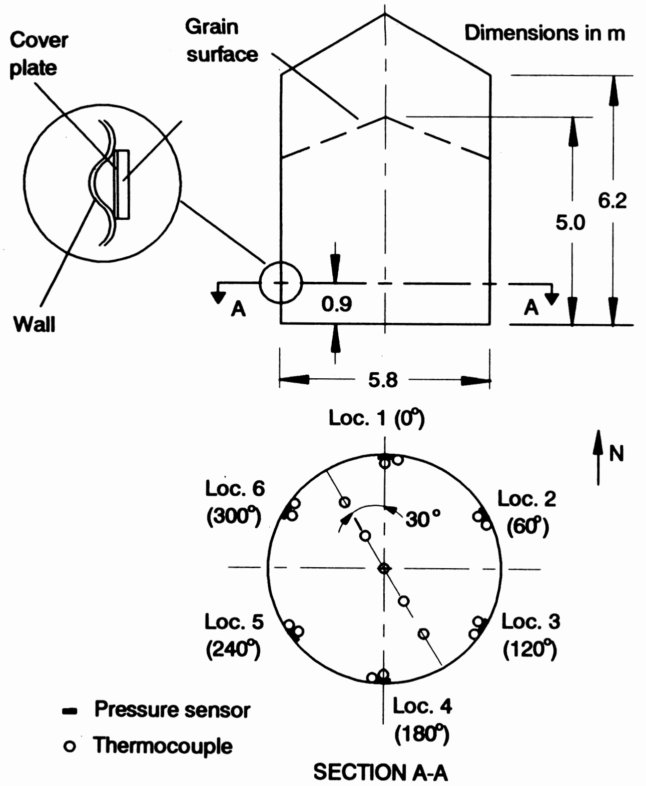

Fig. 1. Test facility and locations of pressure sensors and thermocouples.

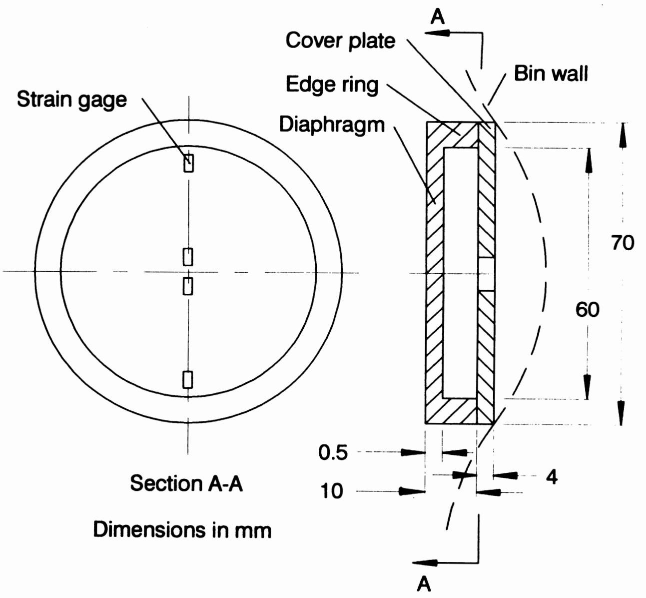

Fig. 2. Schematics of diaphragm pressure sensor.

elevation as the pressure sensors, equally spaced along a bin diameter oriented N 30°W (Fig. 1).

Diaphragm pressure sensor

To achieve high sensitivity, aluminum (6061-T6), which has a low modulus of elasticity, was chosen as the diaphragm material. The diaphragm was created by machining an aluminum disk 10 mm thick and 82 mm in diameter. The finished diaphragm had a thickness of 0.5 mm and a diameter of 60 mm, with an edge ring of 70 mm diameter (Fig. 2). Four strain gages were mounted on the diaphragm along a diameter and the gages were connected in a full-wheatstone bridge.

Each diaphragm sensor was calibrated using a water column at a constant temperature of 19°C. The water column provided a maximum pressure of 4.9 kPa with an accuracy of 10 Pa. Calibration results are summarized in Table II. It was observed that output signals from the diaphragm sensors drifted slightly as temperature changed, even though the strain gages were temperature compensated for aluminum and the four gages were connected in a full-wheatstone bridge. This might be attributed to: (1) the imperfections in the temperature compensation, and (2) slight misalignment of strain gages. To compensate for the temperature effect, temperature calibration was performed. Pressure sensors, without pressure being applied on them, were placed in an environmental chamber. Temperature in the environmental chamber was then reduced from 10 °C to -12 °C in steps of 2 °C/h. Temperature calibration constants for all six sensors are summarized in Table II.

Table I. Physical properties of wheat used in experiment

Bulk density	80 kg/m^3
Filling angle of repose	25.4°
Grain-corrugated wall friction	0.43
Moisture content	10.0% wb

Test period

The experiment ran for 23 consecutive days starting on 3 February 1990. The bin was filled between 16:00 and 17:00 h when the ambient air temperature was about -13 °C. The general weather data (maximum and minimum daily temperatures, and total hours of bright sunshine during the day) for the test period are shown in Fig. 3. During the experiment, pressures and temperatures were recorded hourly using an HP 3852A data acquisition system (Hewlett-Packard, Palo Alto, CA) controlled by a microcomputer.

RESULTS AND DISCUSSION

Static pressure

Lateral pressure on the bin wall was continuously recorded from the beginning of filling. The pressure did not stabilize immediately after filling. To allow the grain to settle to a stable state and to allow the transducers to reach a temperature in equilibrium with the adjacent grain, static pressure readings were taken 24 h after filling, when the average wall temperature was within 1 °C of that immediately after filling. The static pressure averaged from the measurements of six pressure sensors was 9.7 kPa, with a standard deviation of 1.4 kPa. Using property parameters in Table I (the filling angle of repose was used to approximate the angle of internal friction, resulting in a lateral to vertical pressure ratio of 0.4), Janssen's (Ketchum 1919) equation predicted a lateral pressure of 9.9 kPa. The close agreement between the measured static pressure and

Table II. Results of pressure and temperature calibrations for six diaphragm pressure sensors

	Pressure calibration		Temperature calibration	
Sensor No.	Constant, (mV/V)/kPa	R^2	Constant, (mV/V)/°C	R^2
1	25.75 (1.05)*	1.00	2.14 (0.16)*	0.94
2	25.56 (0.85)*	1.00	1.97 (0.10)*	0.90
3	31.25 (0.92)*	0.97	0.41 (0.025)*	0.96
4	25.75 (0.97)*	1.00	1.74 (0.086)*	0.99
5	28.93 (1.45)*	0.99	1.49 (0.071)*	0.98
6	27.08 (1.79)*	1.00	0.55 (0.041)*	0.99

* standard deviation

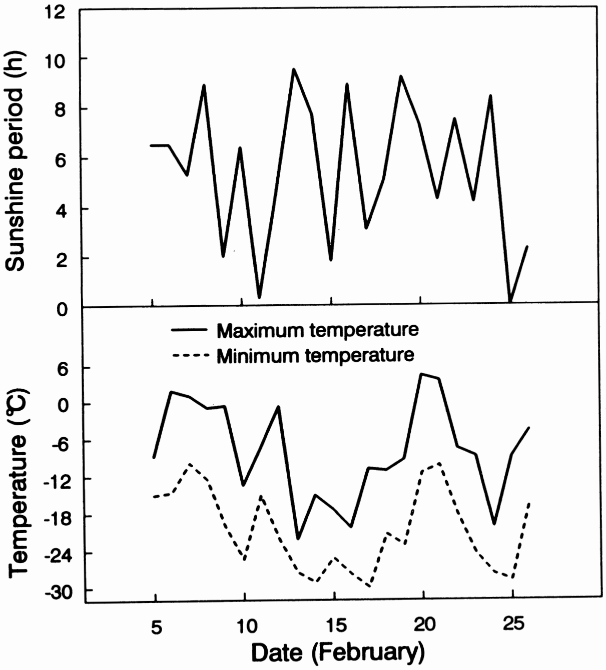

Fig. 3. Maximum and minimum daily temperatures and daily sunshine period for the test days. (The sunshine period is accumulated hours of bright sunshine during the day, recorded at a weather station about 20 km east of the test site).

Janssen's prediction confirmed that the diaphragm sensors adequately measured the lateral pressures on the bin wall.

Thermal pressure

Typical variations of thermal pressure and wall temperature are shown in Fig. 4 for Location 3 (S 60° E). Both thermal pressure and wall temperature fluctuated diurnally. Lower pressures occurred during the daytime when wall temperatures rose and higher pressures occurred during the nighttime when the wall temperatures declined. Negative thermal pressures occurred when the wall temperature rose above the initial wall temperature. The trends for the other locations were similar; however, the magnitudes of fluctuations of thermal pressures and wall temperatures were location dependent. The greatest fluctuations in pressure and wall temperature were observed at Location 4 (S) and the least at Location 1 (N).

Temperature of the south facing surface fluctuated more than other sides during clear days because of the incident solar radiation. During the 23-day test period, the measured range of the south surface temperature was from -27.8 to 45.0 °C, while the recorded range of ambient temperature was from -30.6 to 3.4 °C. In contrast, the fluctuation in temperature of the north facing surface was from -28.5 to 6.9 °C. Temperature fluctuations measured at other locations were between those observed on the south and north facing surfaces. Large fluctuations in wall temperature did not noticeably affect grain temperatures in the interior of the bin. The maximum change in grain temperatures measured at five interior locations was 2.1 °C, or 3% of the maximum fluctuation in the south wall temperature.

The larger fluctuation in wall temperature of the south facing surface caused a larger fluctuation in thermal pressure on the south surface than on other surfaces. Figure 5 shows a typical comparison between the north and the south surface for a 5-day period. Fluctuations in thermal pressures at other locations were between those observed on the north and south surfaces. When the thermal pressure on the south surface became considerably lower than that on the north surface during the daytime on clear days, a non-uniform pressure distribution was induced around the bin circumference. Figure 6 shows a typical comparison of thermal pressure

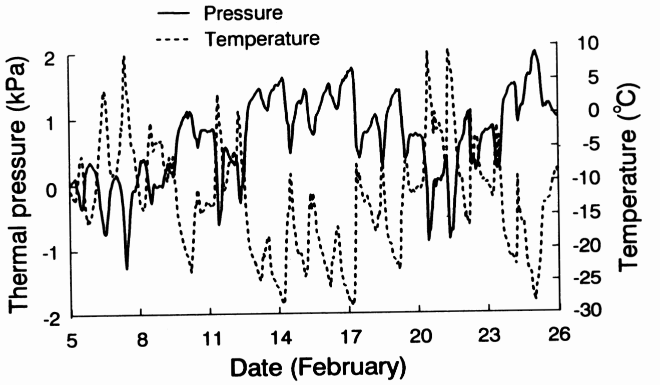

Fig. 4. Lateral thermal pressure and wall temperature in a corrugated-steel bin 5.8 m in diameter and 6.2 m in height, measured at Location 3 (S 60° E).

Table III. Analysis of variance for thermal pressures measured at six locations around the circumference 0.9 m above the bin floor.

	Thermal pressure (kPa)			
	00:00 h		12:00 h	
Location	Mean	St. dev.	Mean	St. dev.
1 (N)	0.85	0.54	0.37	0.70
2 (N 60° E)	1.06	0.82	1.70	0.97
3 (S 60° E)	0.93	0.84	-1.44	2.49
4 (S)	0.98	1.03	-2.86	2.15
5 (S 60° W)	0.77	0.54	0.20	0.71
6 (N 60°W)	0.81	0.52	0.42	1.02
F-Statistic	0.45		23.88	
Rejection region (α=0.05)	2.29		2.29	

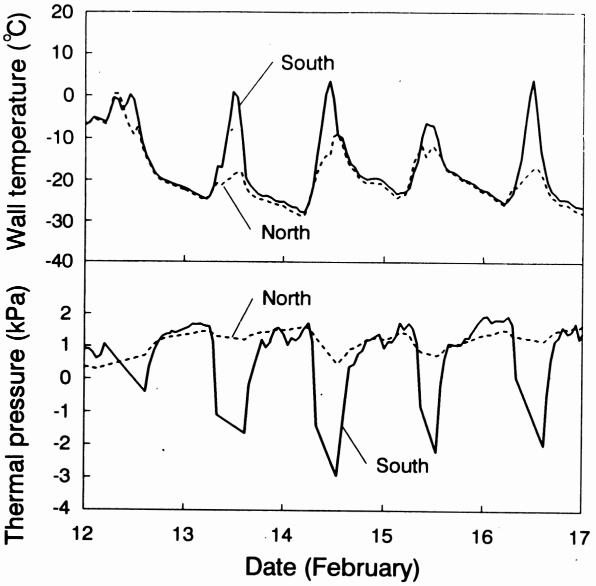

Fig. 5. Lateral thermal pressure and wall temperature on the south and north facing surfaces of a corrugated-steel bin 5.8 m in diameter and 6.2 m in height for a 5-day period.

distribution between the noon hour (12:00 h) and mid-night (00:00 h) for clear days. Each data point represented the average temperature at 12:00 or 00:00 h for days when there was at least 6 h of bright sunshine (total 10 days out of 23). The difference in the daily temperature (Fig. 3) caused large variations in thermal pressures as indicated by the large standard deviations. In spite of these large variations, the analysis of variance indicated that the thermal pressures measured at Locations 3 (S 60° E) and 4 (S) were significantly lower than those measured at other locations at 12:00 h (Table III). Although the lower pressure would result in lower hoop tension stress and lower vertical compression stress in the south facing portion of the bin, the non-uniform pressure distribution might impose a greater potential of structural failure because non-symmetrical pressures may cause buckling failures even if the tension and compression stresses in the bin wall are below the yield stress of the wall material.

During the nighttime, the bin wall temperature was uniform. Variation in wall temperatures measured at six locations was within 1.6 °C. Consequently, the difference in thermal pressure between six locations for 00:00 h was insignificant ($P > 0.05$) (Table III).

Thermal pressure coefficients, C_t, defined as the thermal pressure per unit decline in wall temperature, were compared between six locations (Fig. 6). Analysis of variance showed that there was no significant ($P < 0.05$) difference in thermal pressure coefficient between six locations at either 12:00 or 00:00 h (Table IV). Since 00:00 and 12:00 h represented typical nighttime and daytime hours when the low and high wall temperatures occurred, respectively, it was concluded that the increase in thermal pressure per unit wall temperature decline was uniform around the bin circumference during both daytime and nighttime. This suggests that the thermal pressures around the bin circumference may be calculated by using a single thermal pressure coefficient and the magnitude of thermal pressure at different locations on the circumference is dictated by the local wall temperature.

A linear model was used to relate the lateral thermal pressure to the wall temperature decline (Puri et al. 1986; Manbeck and Muzzelo 1985):

$$p_t = C_t \Delta T \qquad (1)$$

where:

p_t = thermal pressure (Pa),

Table IV. Analysis of variance for thermal pressure coefficients (thermal pressure per unit wall-temperature decline) measured at six locations around the circumference 0.9 m above the bin floor.

	Thermal pressure coefficient (kPa/°C)			
	00:00 h		12:00 h	
Location	Mean	St. dev.	Mean	St. dev.
1 (N)	0.019	0.41	0.61	0.45
2 (N 60° E)	0.13	0.71	0.091	0.96
3 (S 60° E)	0.15	0.54	0.14	0.47
4 (S)	0.19	0.53	0.21	0.39
5 (S 60° W)	0.13	0.44	0.057	0.37
6 (N 60° W)	0.073	0.41	0.083	0.30
F-Statistic	0.30		0.38	
Rejection region (α=0.05)	2.29		2.29	

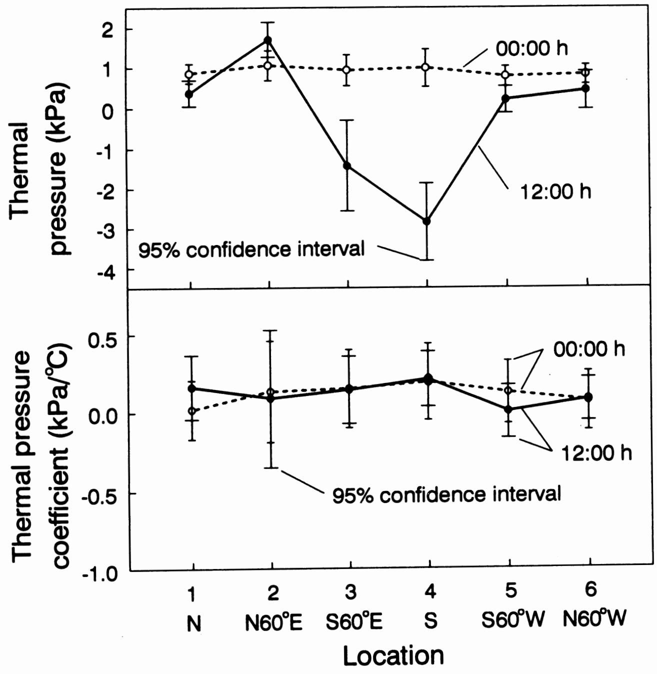

Fig. 6. Mean thermal pressure distribution around the bin circumference, 0.9 m above the floor, at 00:00 and 12:00 h for 10 clear days.

C_t = thermal pressure coefficient (Pa/°C), and

ΔT = wall temperature drop (°C).

The average thermal pressure coefficient was determined by performing regression analysis on data pooled from the measurements of all six pressure sensors. The value was 114 Pa/°C with a standard deviation of 2 Pa/°C for a range of bin wall temperature from -11 to -29 °C (18 °C temperature drop). Data corresponding to wall temperatures higher than the initial wall temperature (-11 °C) were excluded in the regression analysis because higher wall temperatures caused lateral pressures lower than the static pressure.

SUMMARY AND CONCLUSIONS

An experiment was conducted using a corrugated galvanized steel bin 5.8 m in diameter and 6.2 m in height to explore the diurnal and circumferential variation of thermal loads in an on-farm grain bin. The bin was instrumented with diaphragm pressure sensors and thermocouples and was filled with wheat at 10.0% wb moisture content to a depth of 5.0 m. Lateral bin-wall pressures and wall temperatures around the bin circumference 0.9 m above the floor, as well as the grain temperature at the same elevation, were measured continuously for 23 days in February, 1990. The thermal pressure-temperature relationship and thermal pressure distribution around the bin circumference were examined. Based on this study, the following conclusions were drawn:

1. Lateral bin-wall pressure in an on-farm grain storage bin fluctuated diurnally. The minimum pressure occurred during the daytime and the maximum during the nighttime. The fluctuation in lateral pressure on the south facing surface was greater than those on other sides.
2. Thermal pressure distribution around the bin circumference (0.9 m above the bin floor) was non-uniform during the daytime, with the pressure on the south facing portion of the bin being significantly lower than those on other sides. The pressure distribution around the bin circumference was uniform during the nighttime hours.
3. Increase in lateral pressure per unit wall-temperature drop did not vary significantly around the bin circumference. The average thermal pressure increment was 114 kPa/°C for up to an 18 °C decline in bin wall temperature.

REFERENCES

Andersen, P. 1966. Temperature stresses in steel grainstorage tanks. *Civil Engineering* (American Society of Civil Engineers) 38:74.

Anonymous. 1984. *Grain Grading Handbook for Western Canada*. Canadian Grain Commission, Winnipeg, MB.

ASAE. 1989. ASAE Standards, 36th edition. St. Joseph, MI: ASAE.

Blight, G.E. 1985. Temperature changes affect overpressures in steel bins. *International Journal of Bulk Solids Storage in Silos* 1(3):1-7.

Britton, M.G. 1973. Strain on deep bin walls due to ambient temperature decrease. Unpublished Ph.D. thesis, Texas A & M, College Station, TX.

Ketchum, M.S. 1919. *The Design of Walls, Bins and Grain Elevators*. New York, NY: McGraw-Hill Book Company Inc.

Kukelko, A.D., D.S. Jayas, N.D.G. White and M.G. Britton. 1988. Physical properties of canola (rapeseed) meal. *Canadian Agricultural Engineering* 30:61-64.

Leitgeb, J.M. 1990. The measurement of thermal pressures in a full size grain bin. Unpublished B.Sc. thesis, The University of Manitoba, Winnipeg, MB.

Manbeck, H.B. 1984. Predicting thermally induced pressures in grain bins. *Transactions of the ASAE* 27(1):482-486.

Manbeck, H. B. and M.G. Britton. 1988. Prediction of bin wall temperature declines. *Transactions of the ASAE* 31(6):1767-1773.

Manbeck, H.B. and L.M. Muzzelo. 1985. Measurement of thermally induced pressures in a model grain bin. *Transactions of the ASAE* 28(4):1253-1264.

Puri, V.M., Q. Zhang and H.B. Manbeck. 1986. Influence of granular material properties on thermally induced bin loads. *International Journal of Bulk Solids Storage in Silos* 2(3):1-7.

Thompson, S.A. and I.J. Ross. 1984. Thermal stresses in steel grain bins using the tangent modulus of grain. *Transactions of ASAE* 27(1):165-168.

Zhang, Q., V.M. Puri, H.B. Manbeck and M.C. Wang. 1987. Finite element model for predicting static and thermally induced bin wall pressures. *Transactions of the ASAE* 30(6):1797-1806.